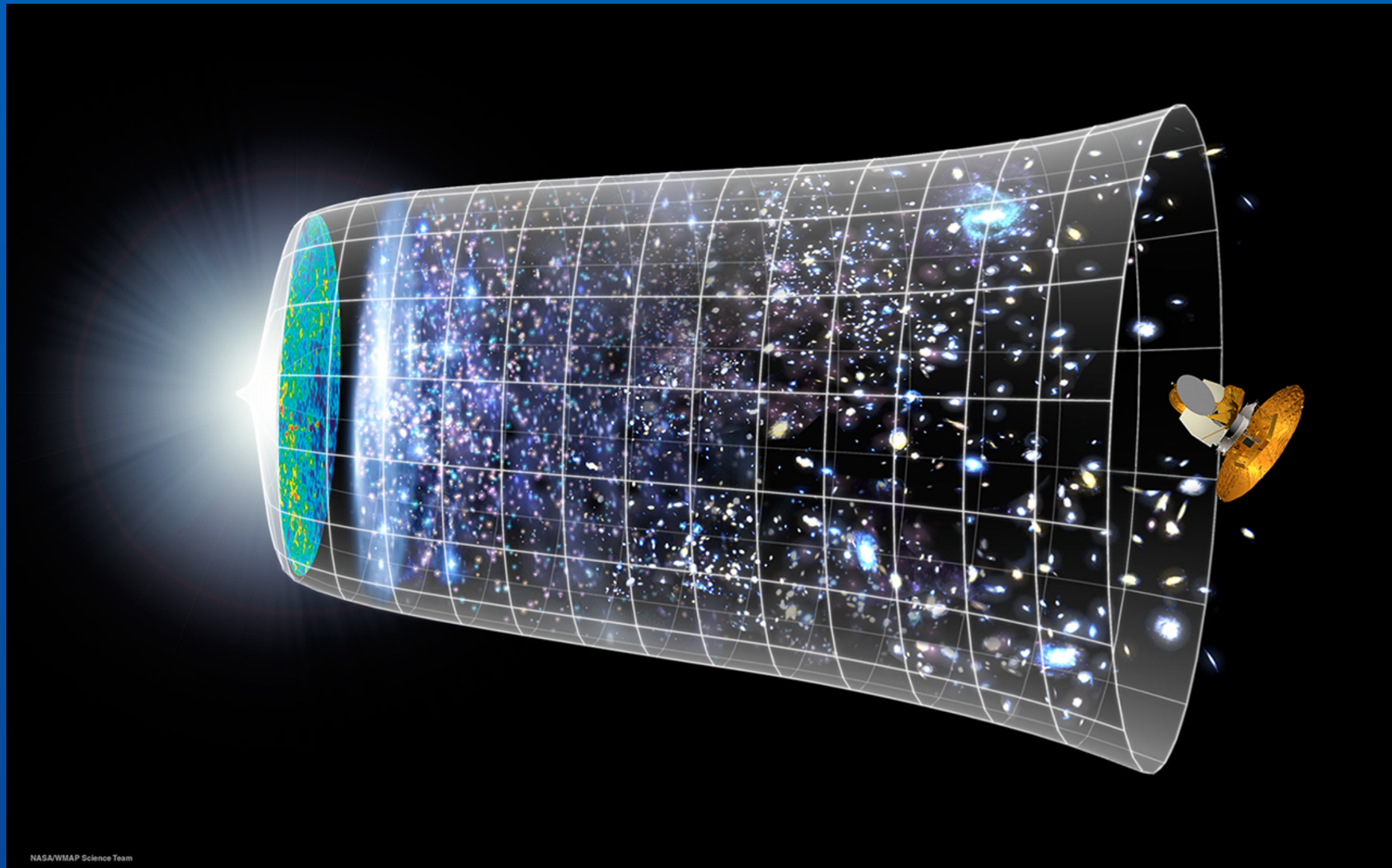


Metamaterial Anti-Reflection Coating Alumina Optics for CMB-S4



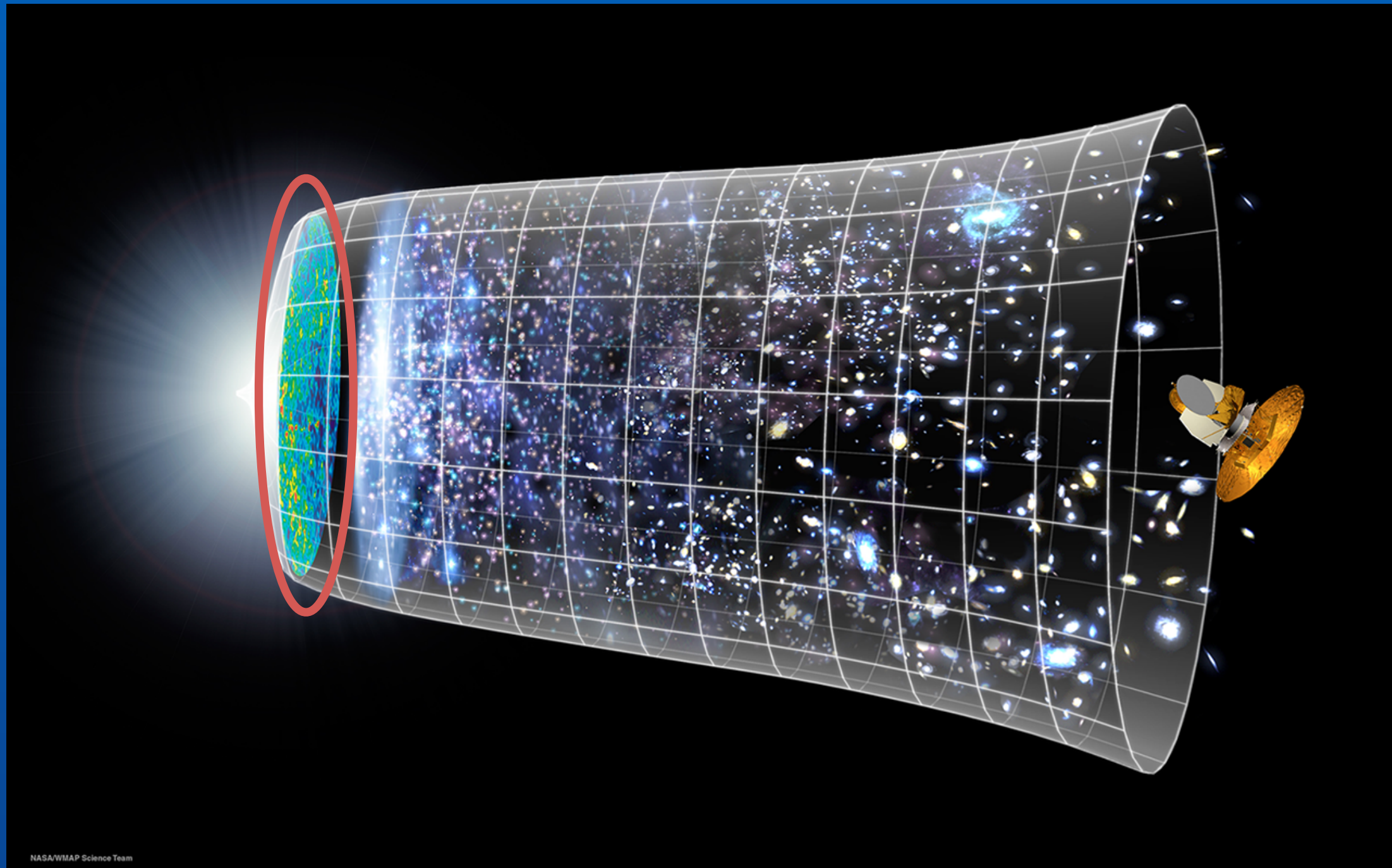
Joey Golec
New Perspectives 2021
8/16/21

The CMB



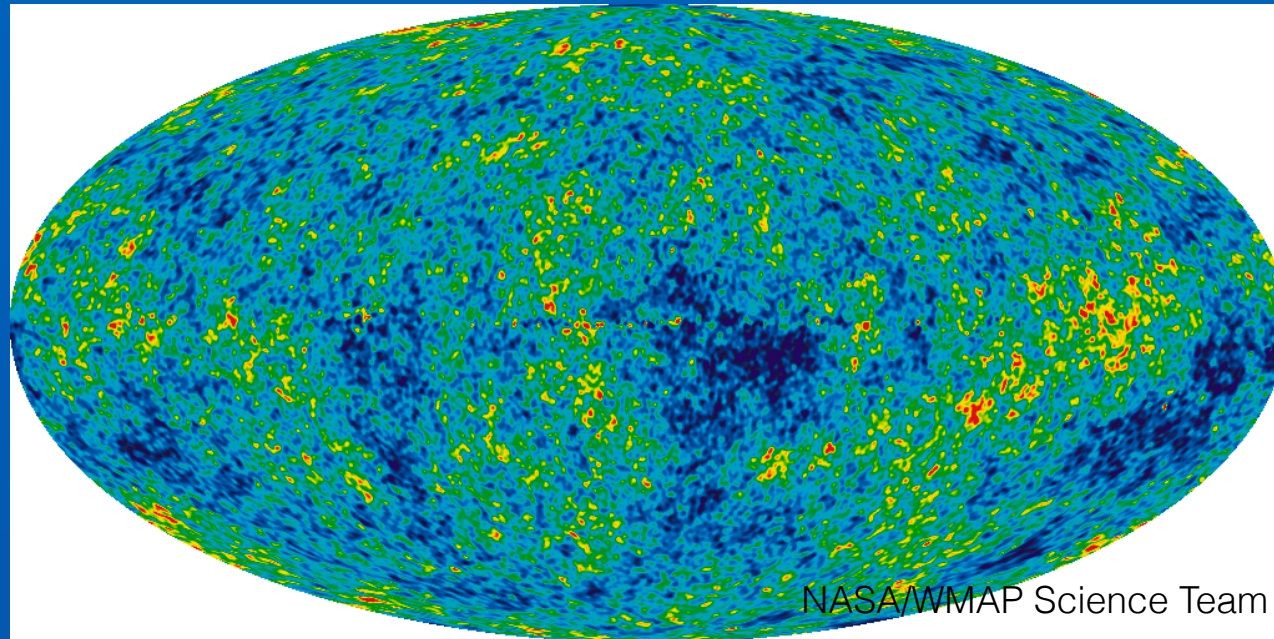
NASA/WMAP Science Team

The CMB

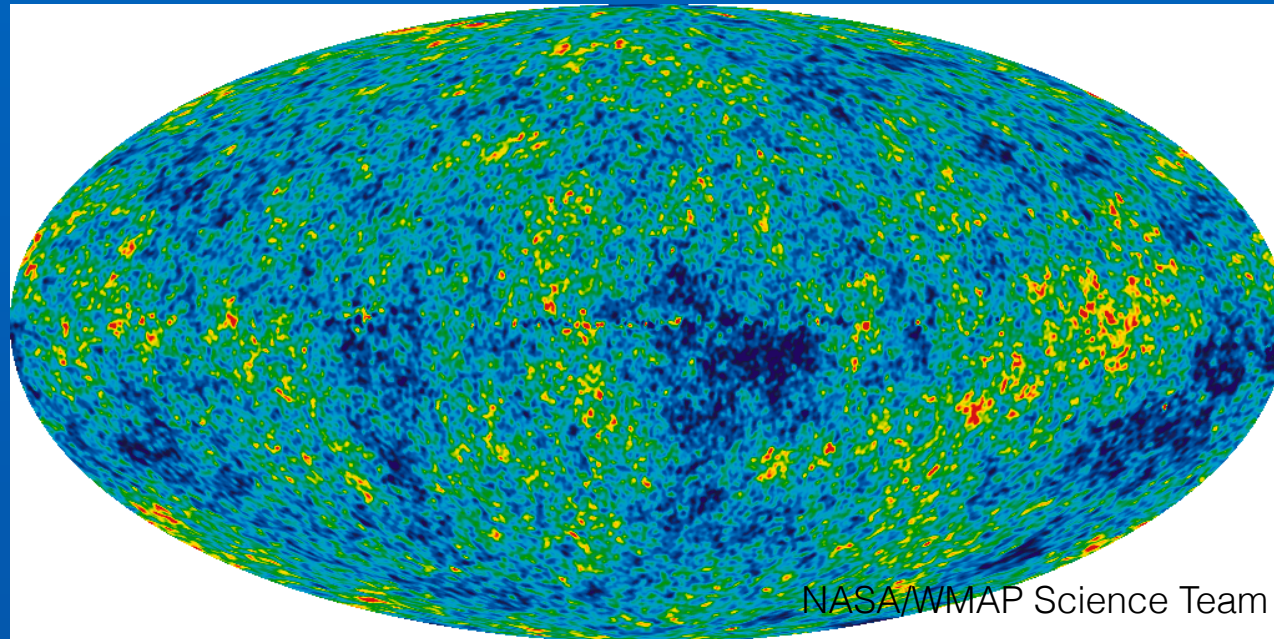


NASA/WMAP Science Team

The CMB

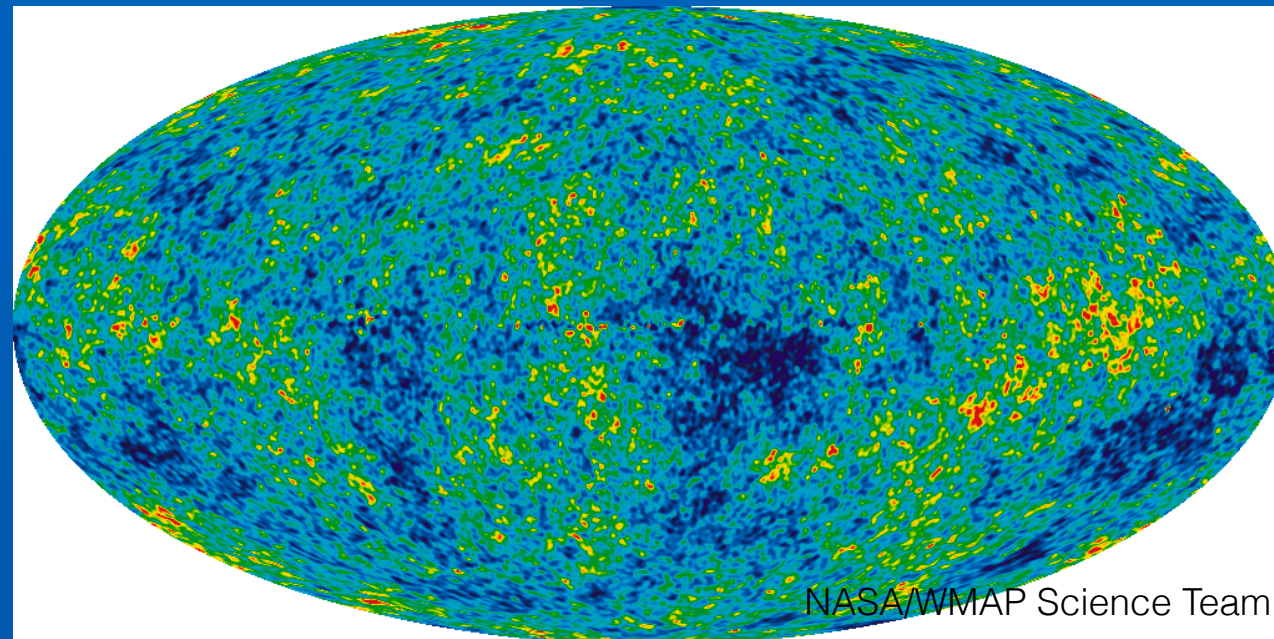


The CMB

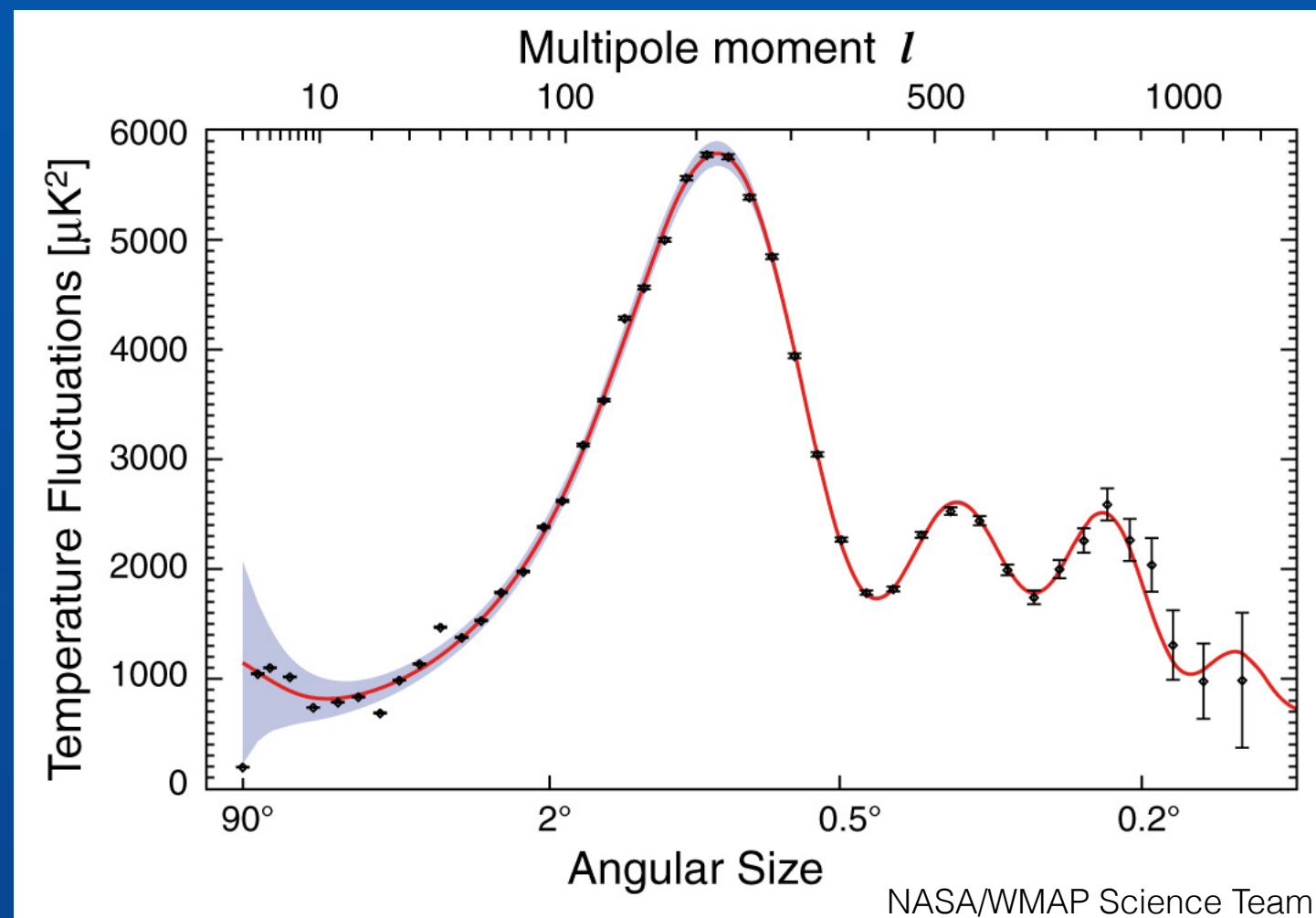


Decompose into spherical harmonics

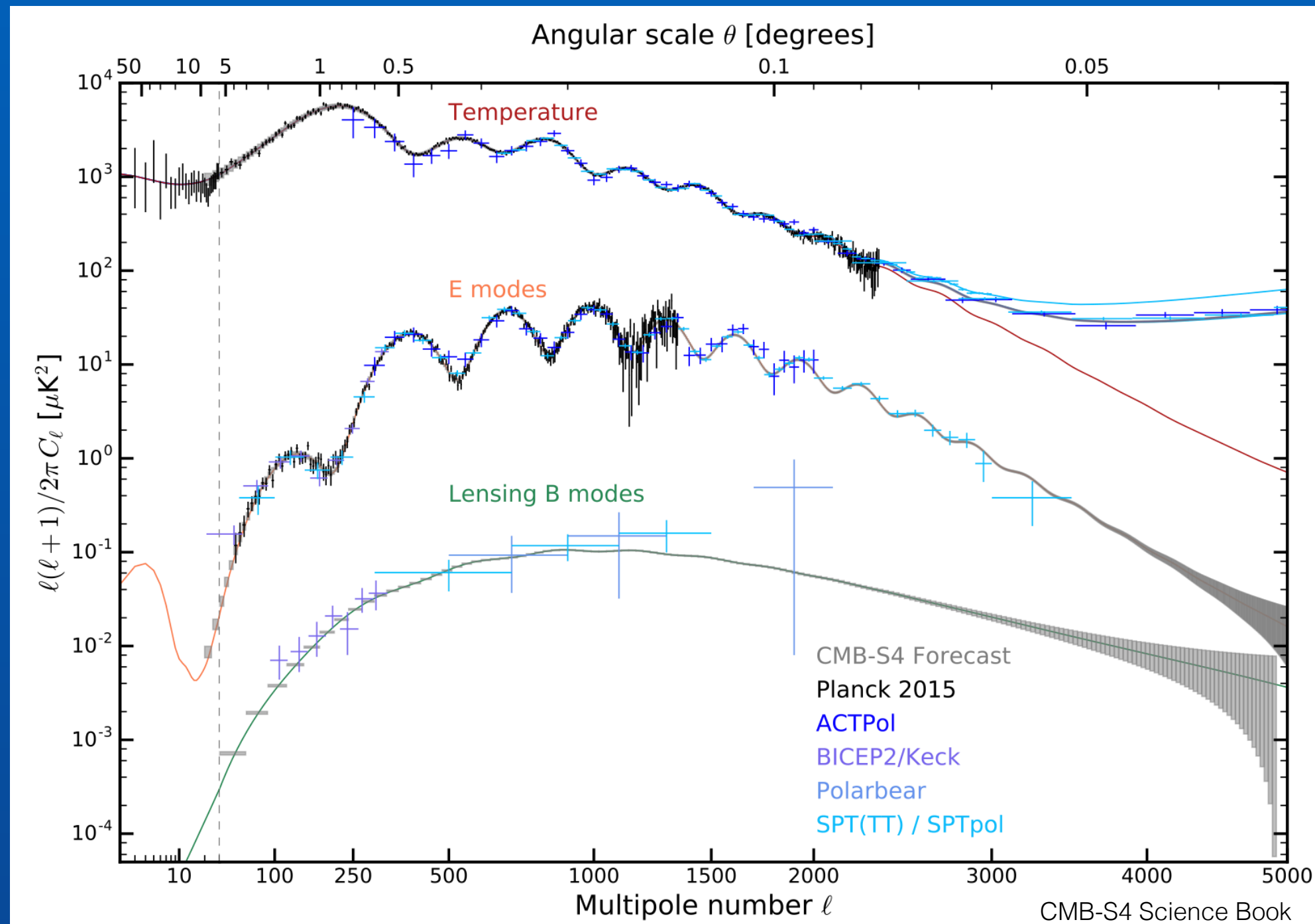
The CMB



Decompose into spherical harmonics

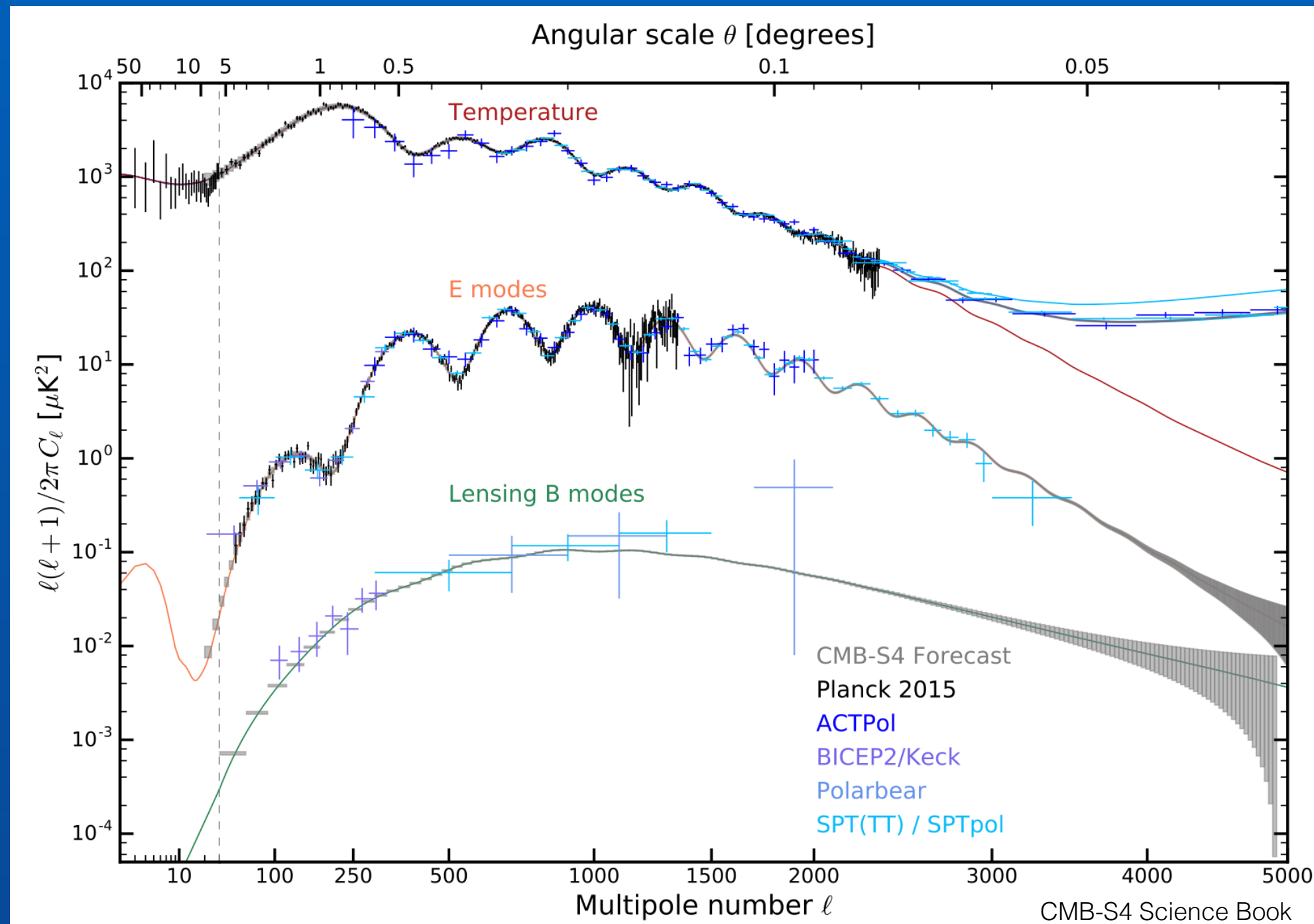


CMB-S4 Science Themes



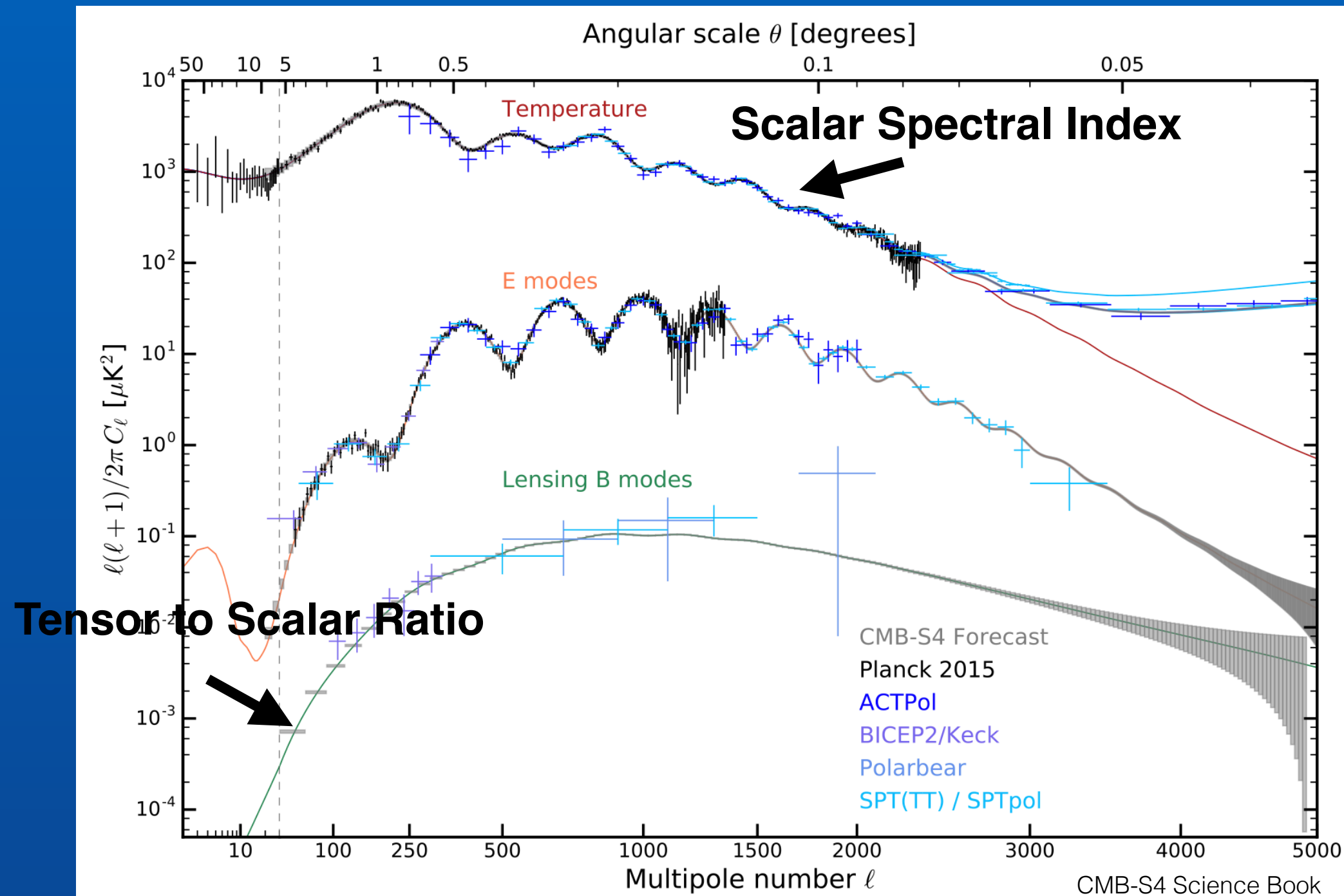
CMB-S4 Science Themes

1. Constrain Inflation



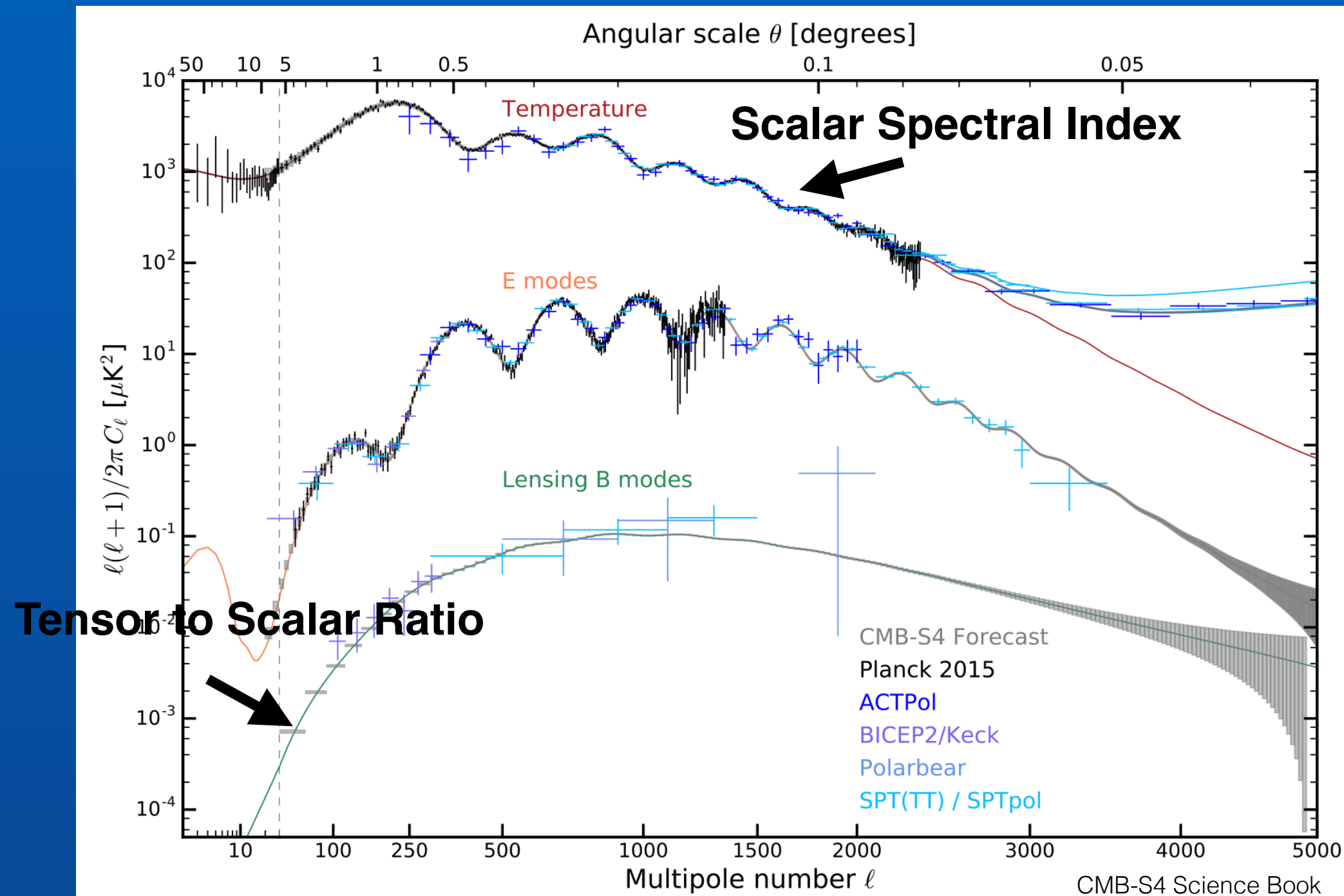
CMB-S4 Science Themes

1. Constrain Inflation



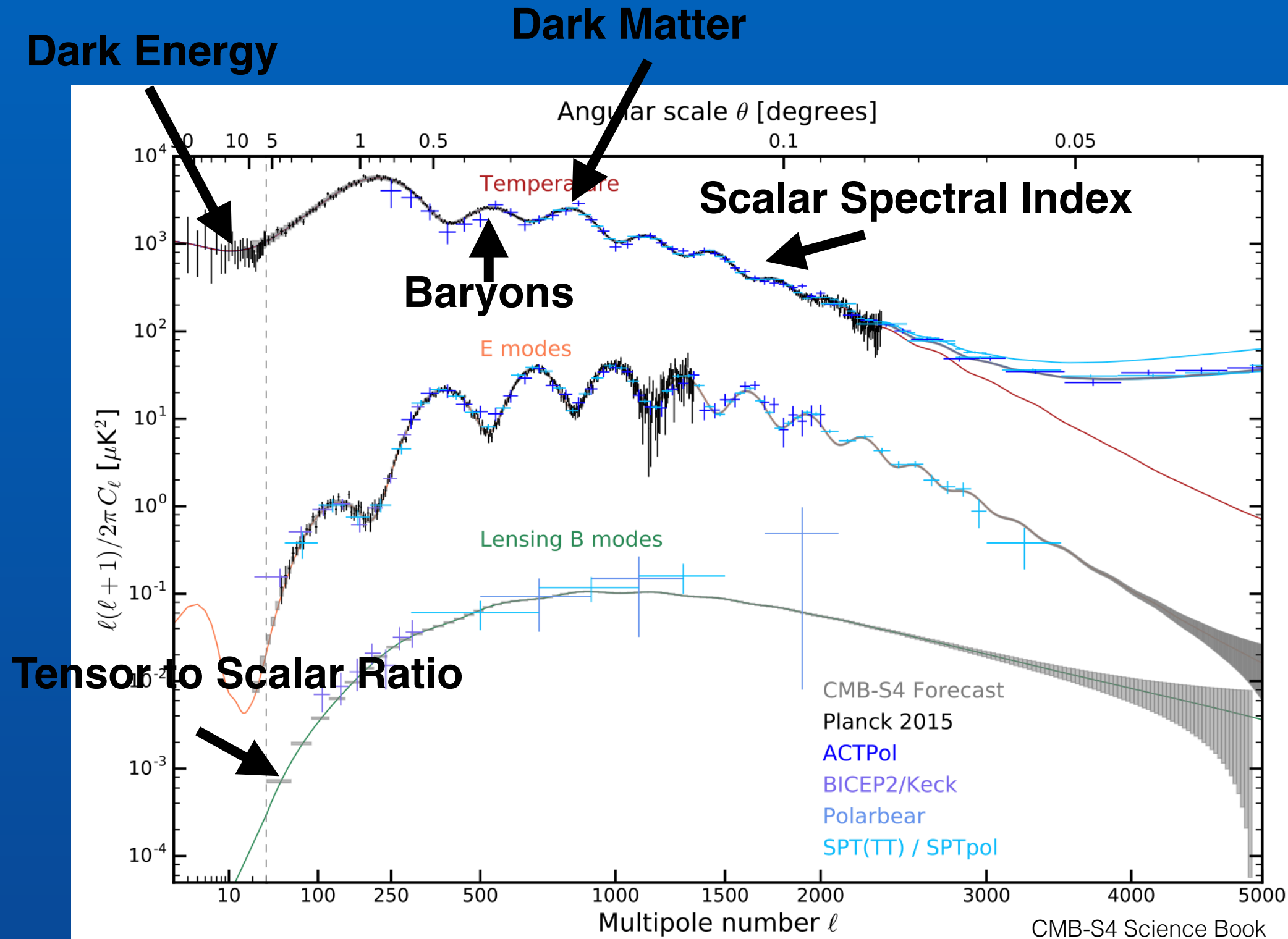
CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe



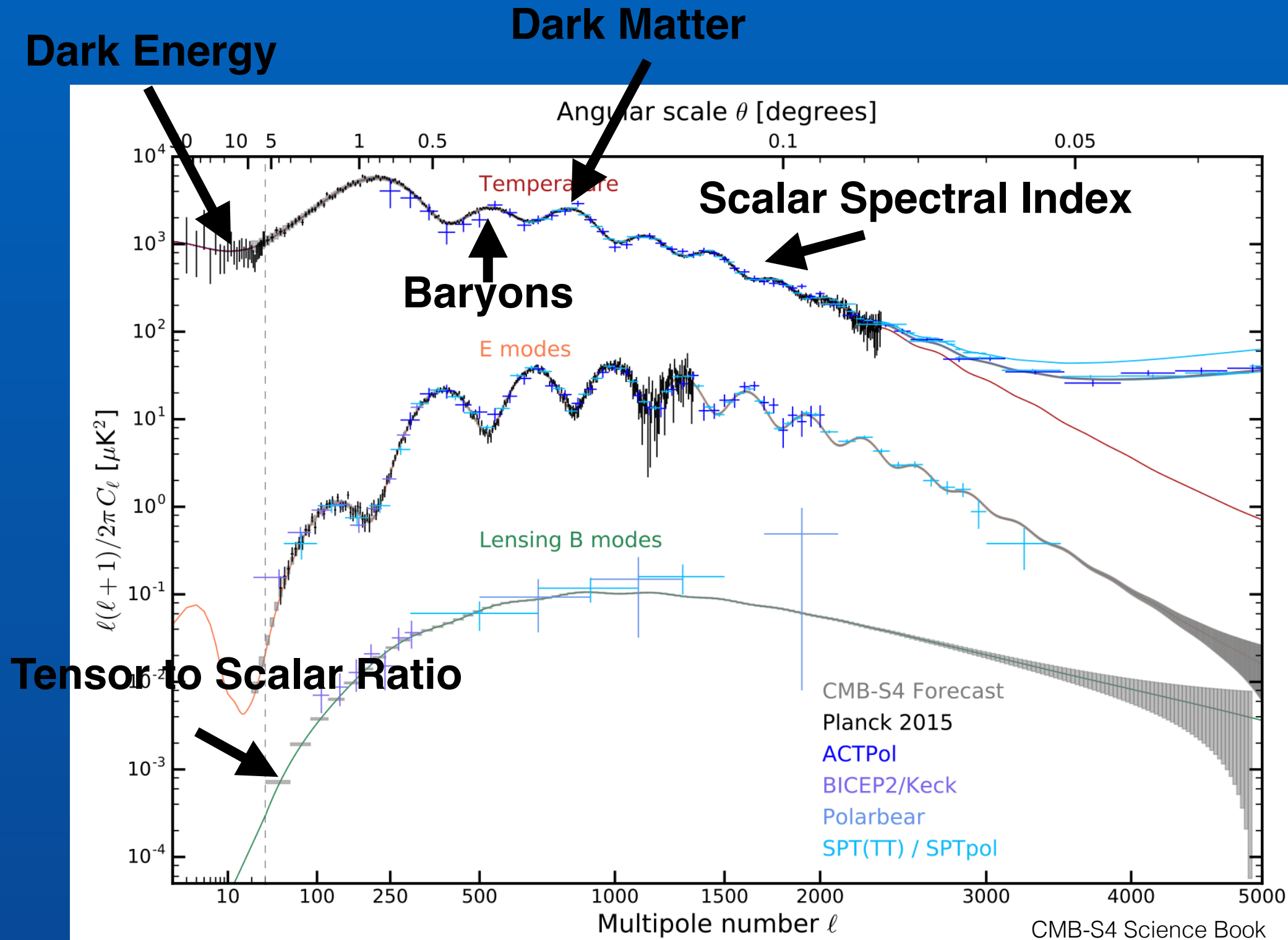
CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe



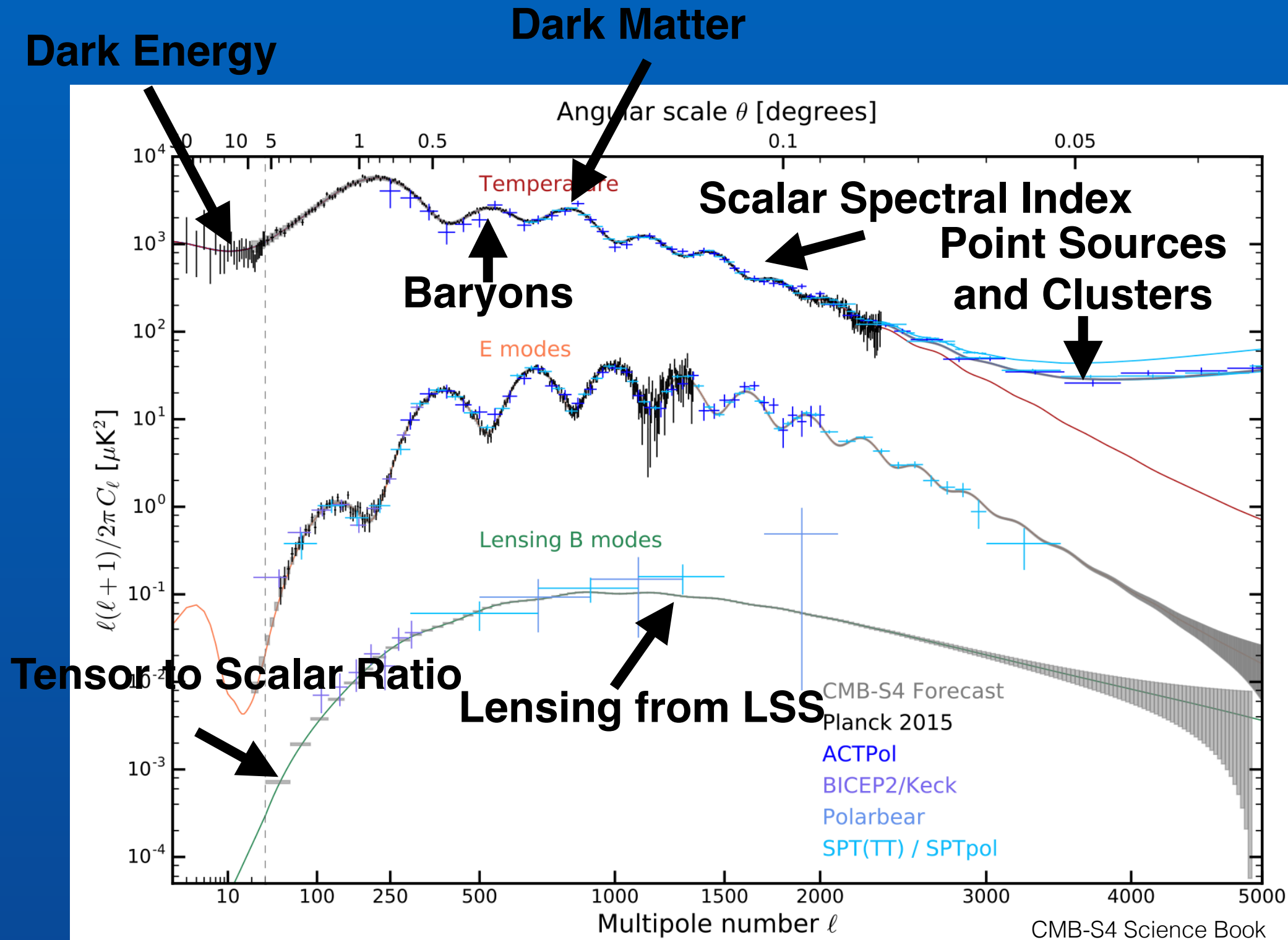
CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe
3. Map the matter distribution in the universe



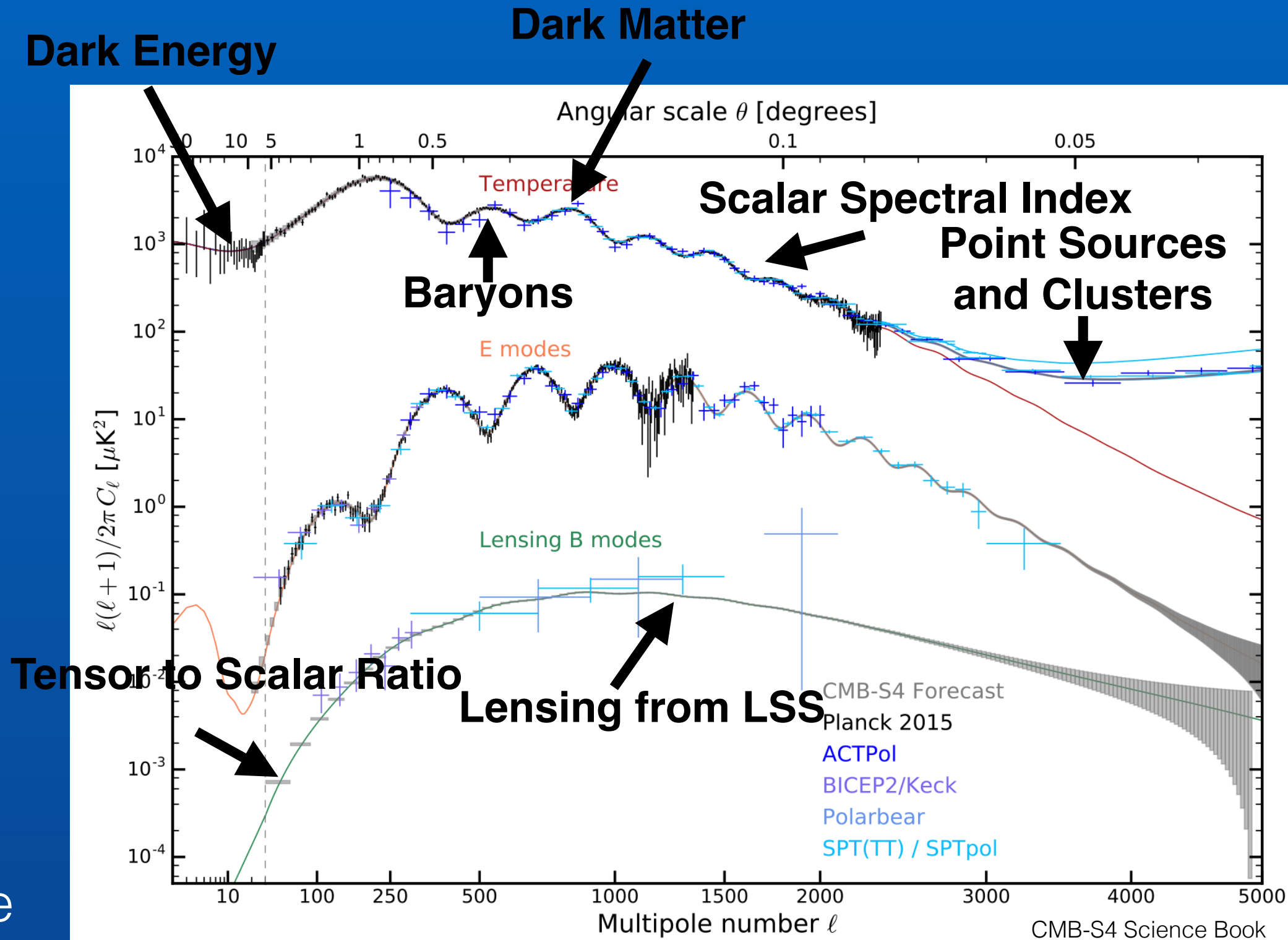
CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe
3. Map the matter distribution in the universe



CMB-S4 Science Themes

1. Constrain Inflation
2. Investigate the “Dark” Universe
3. Map the matter distribution in the universe
4. Investigate millimeter-wave transients



CMB-S4

Goal

1. Constrain Inflation

2. Investigate the “Dark” Universe

3. Map the matter distribution through lensing

4. Investigate millimeter-wave transients



- Large Survey Area
- Extremely Deep Survey
- Low Angular Resolution
- Sensitive at Large Angular Scales

- Large Survey Area
- Extremely Deep Survey
- High Angular Resolution

- Large Survey Area
- Extremely Deep Survey
- High Angular Resolution

- Largest Survey Area Possible
- Extremely Deep Survey
- High Angular Resolution
- High Cadence Scans



Small Aperture Telescopes at the South Pole

Large Aperture Telescopes at the Atacama and the South Pole

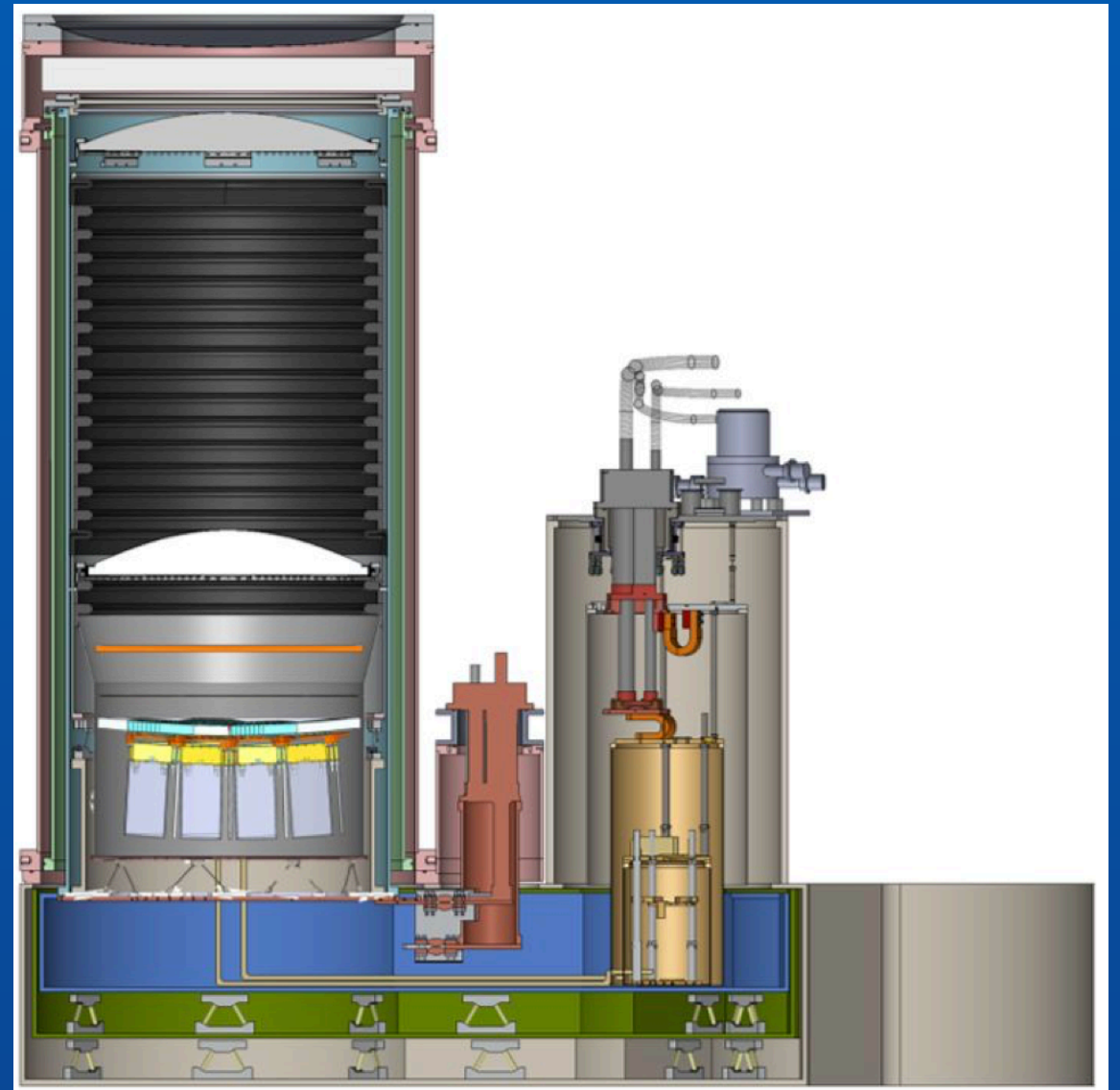
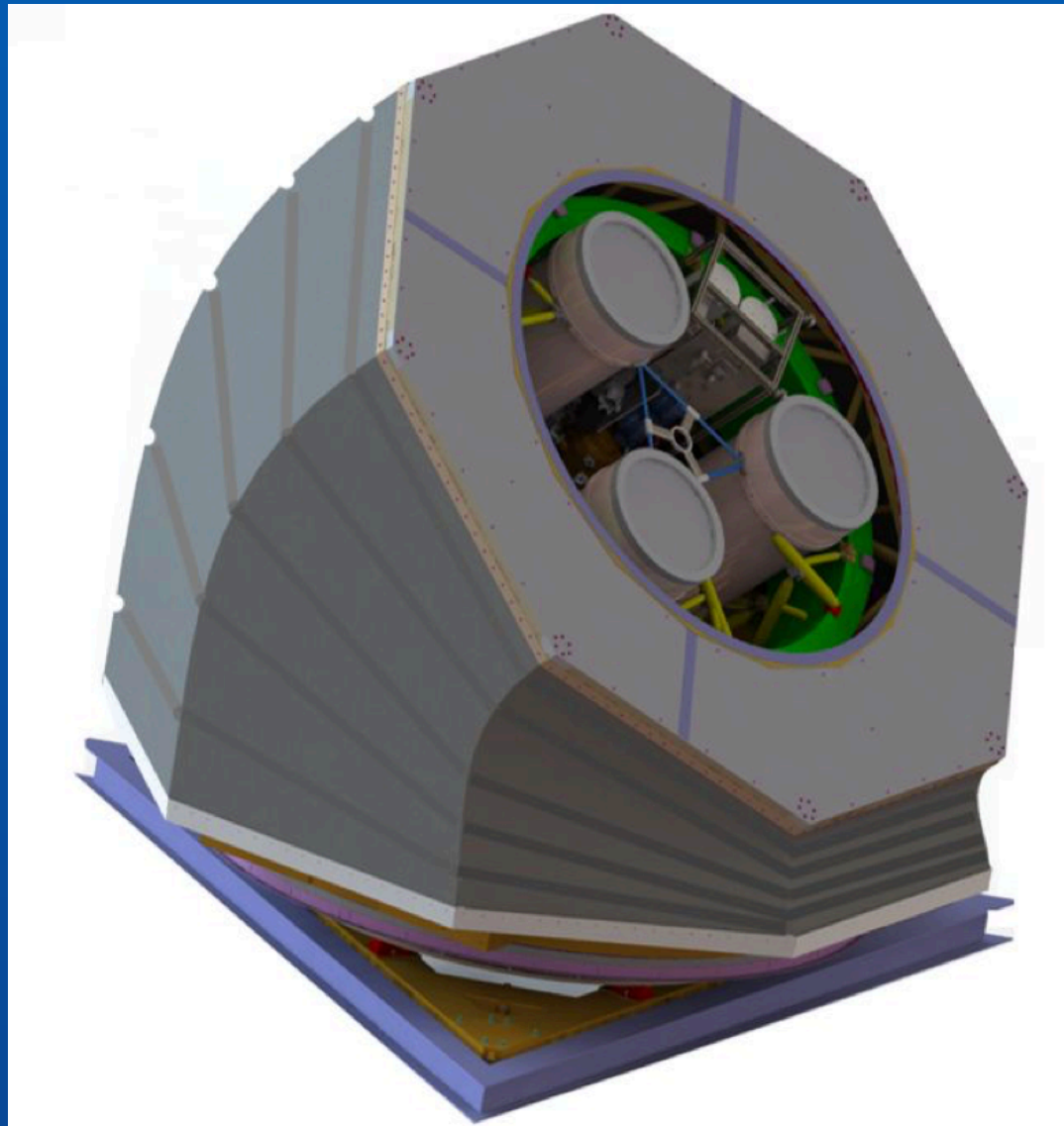
Large Aperture Telescope in Atacama

Instrument Solution

CMB-S4 Instruments

Instrument
Solution

Small
Aperture
Telescopes

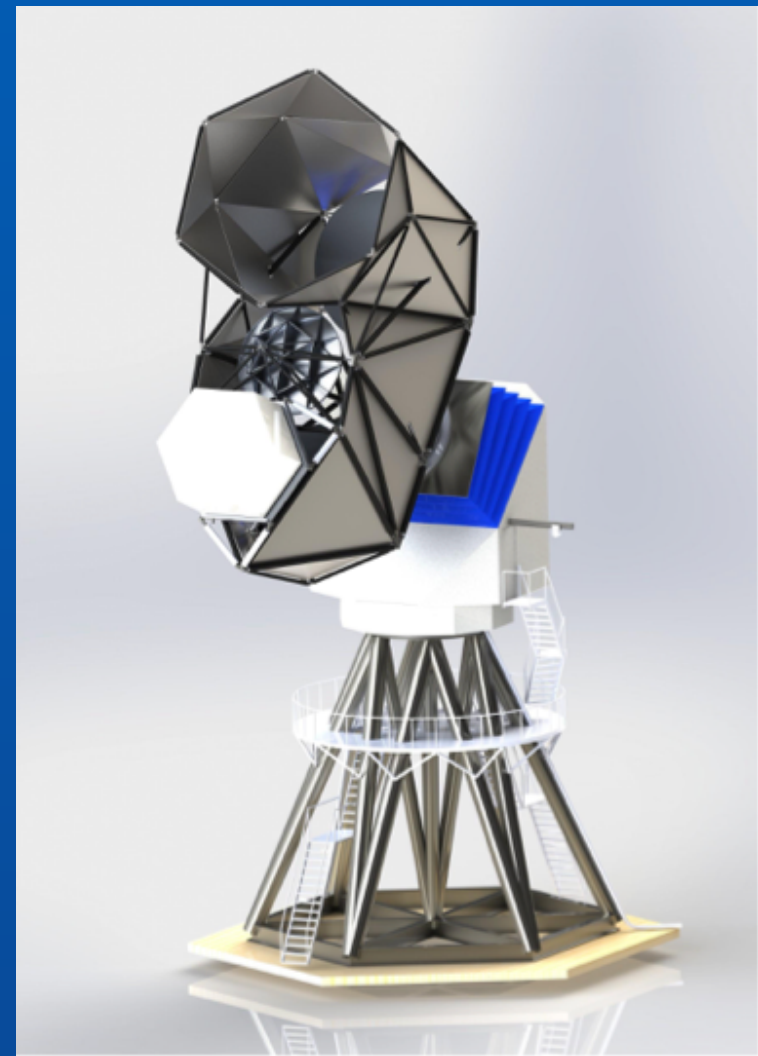
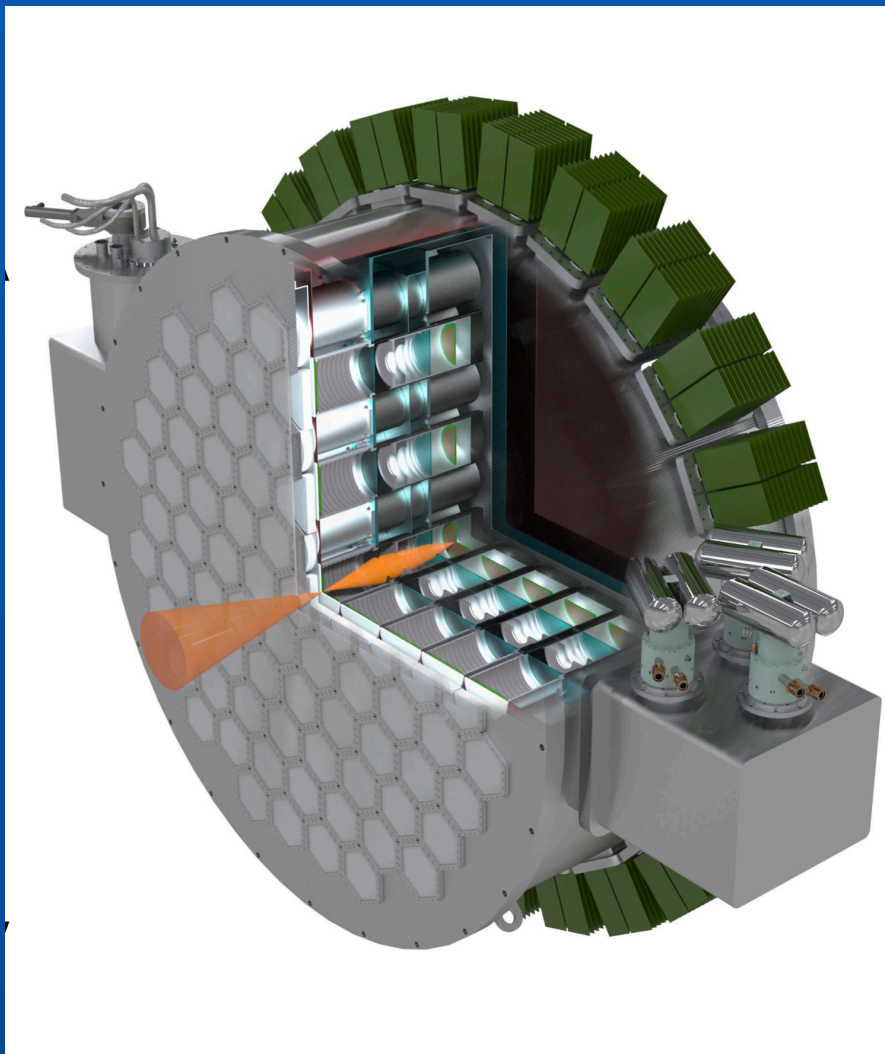
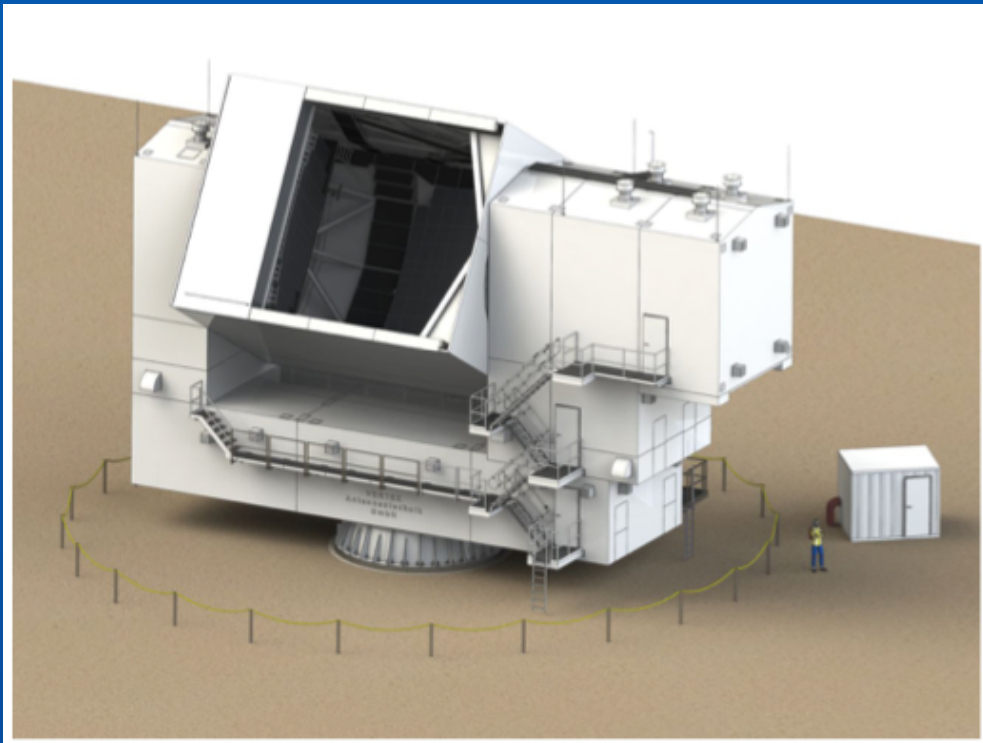


Both images from CMB-S4 Spring 2021 Workshop (J. Kovac)

CMB-S4 Instruments

Instrument
Solution

Large
Aperture
Telescopes



Optical Requirements

- CMB-S4 will require hundreds of optical elements for all of its instruments
- Highly transparent optics are required to collect more photons and mitigate instrument systematics
- S4 will require >100 alumina filters alone

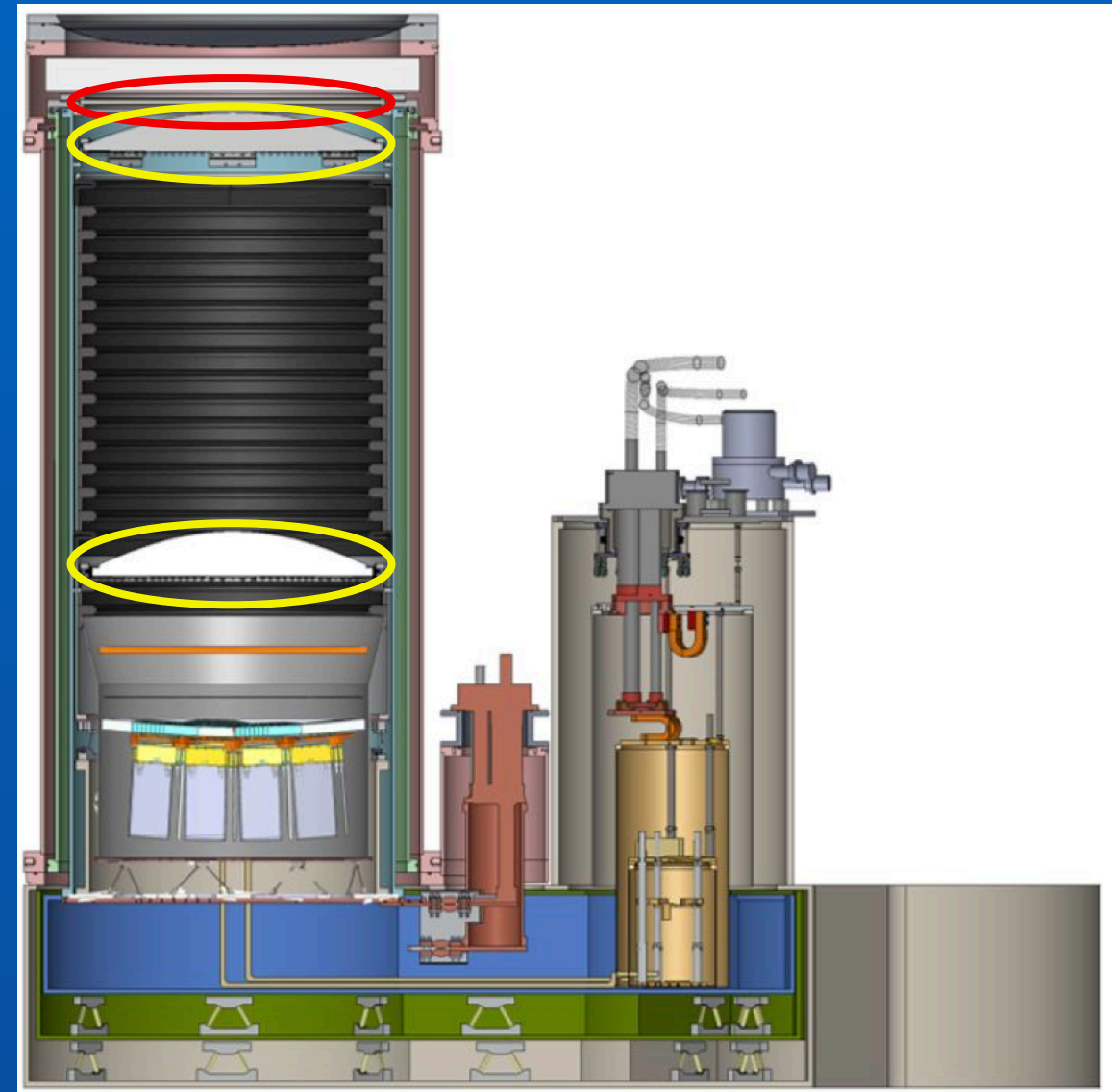


Image from CMB-S4 Spring 2021 Workshop (J. Kovac)

x18

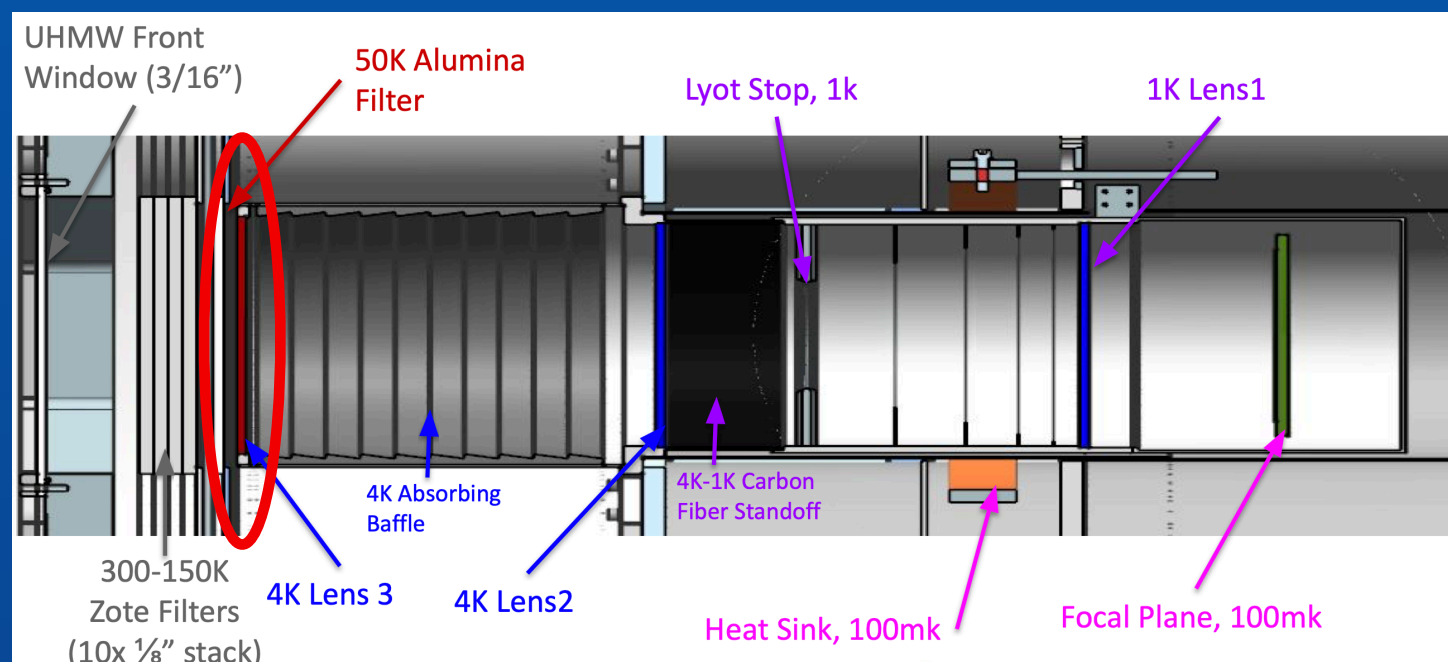


Image from CMB-S4 Spring 2021 Workshop (D. Mitchell)

x85

Alumina Optics

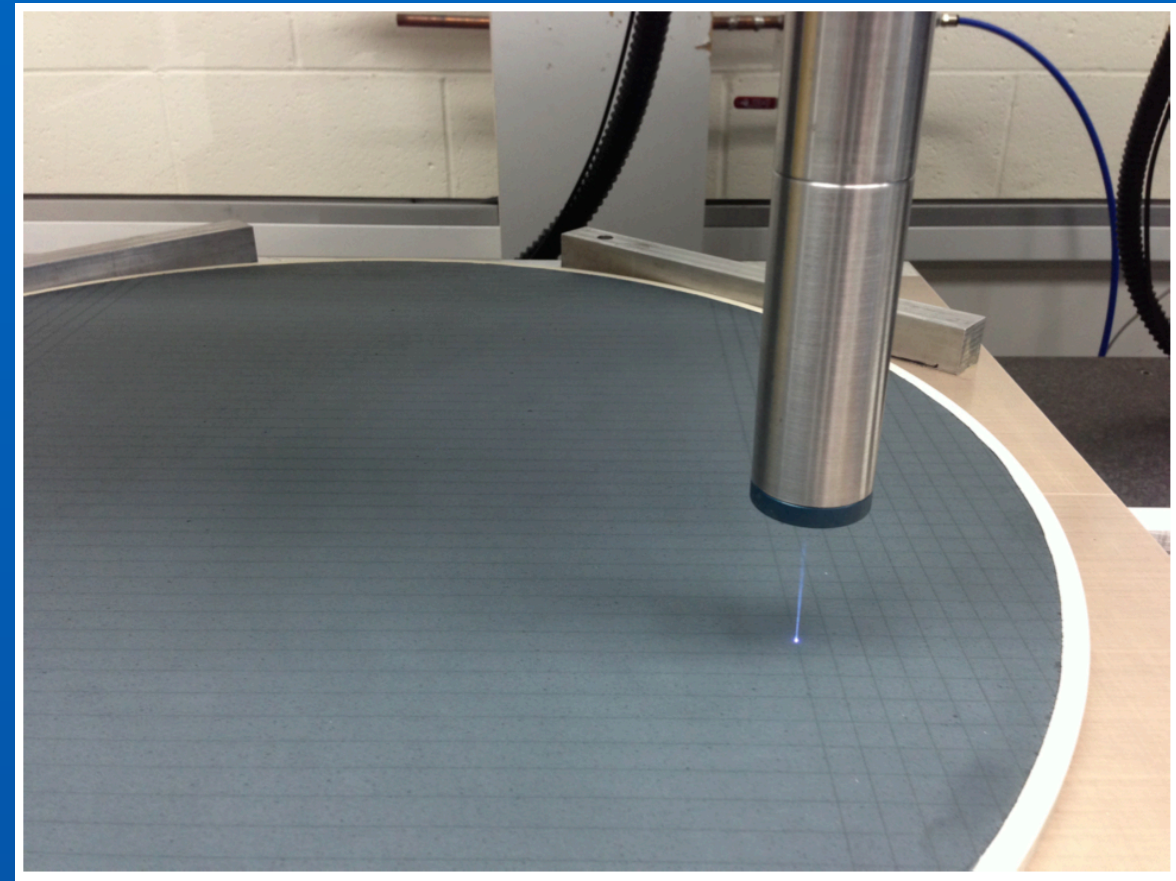
- Alumina has great optical properties at millimeter wavelengths
- Low transmission at IR frequencies makes alumina a good filter
- Current experiments like SPT-3G and BICEP3 use alumina lenses
- Existing AR coating methods are lossy and can suffer from cryomechanical failures

SPT-3G Lens

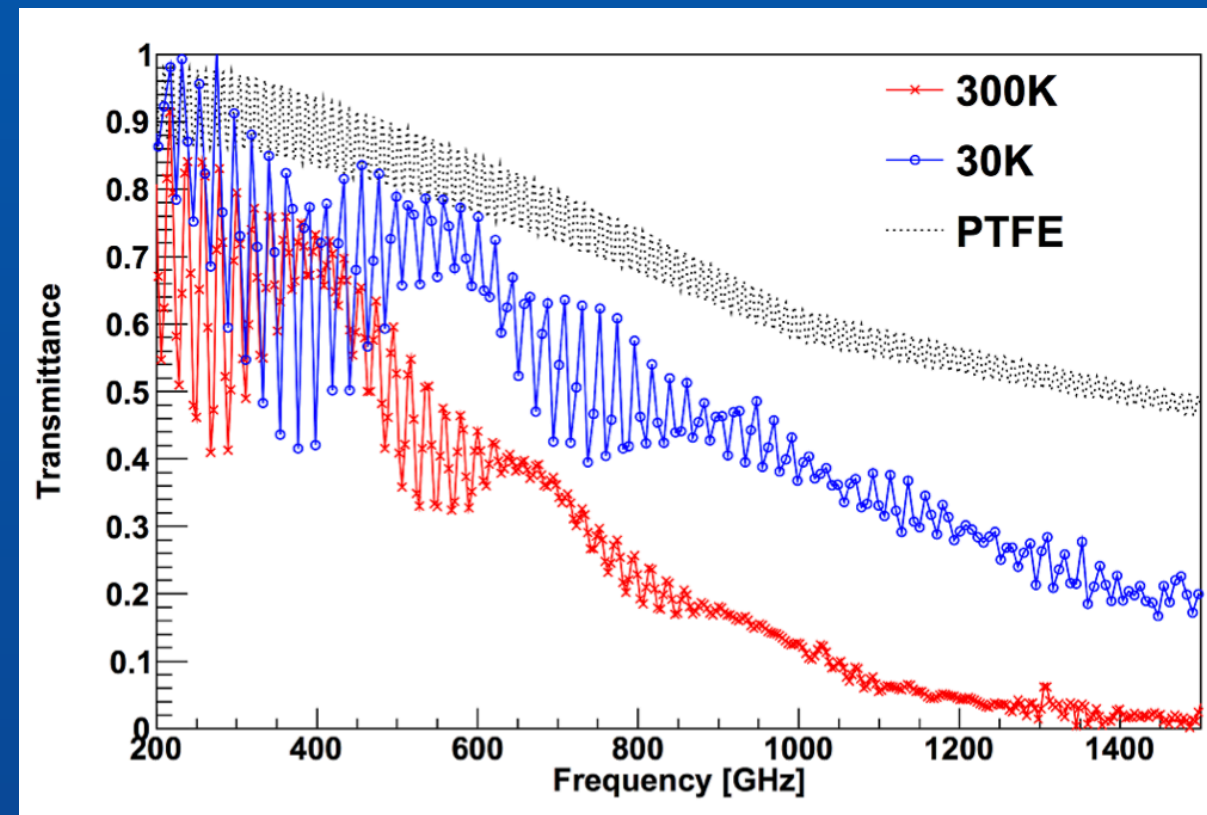


A. Nadolski et al. (2018)

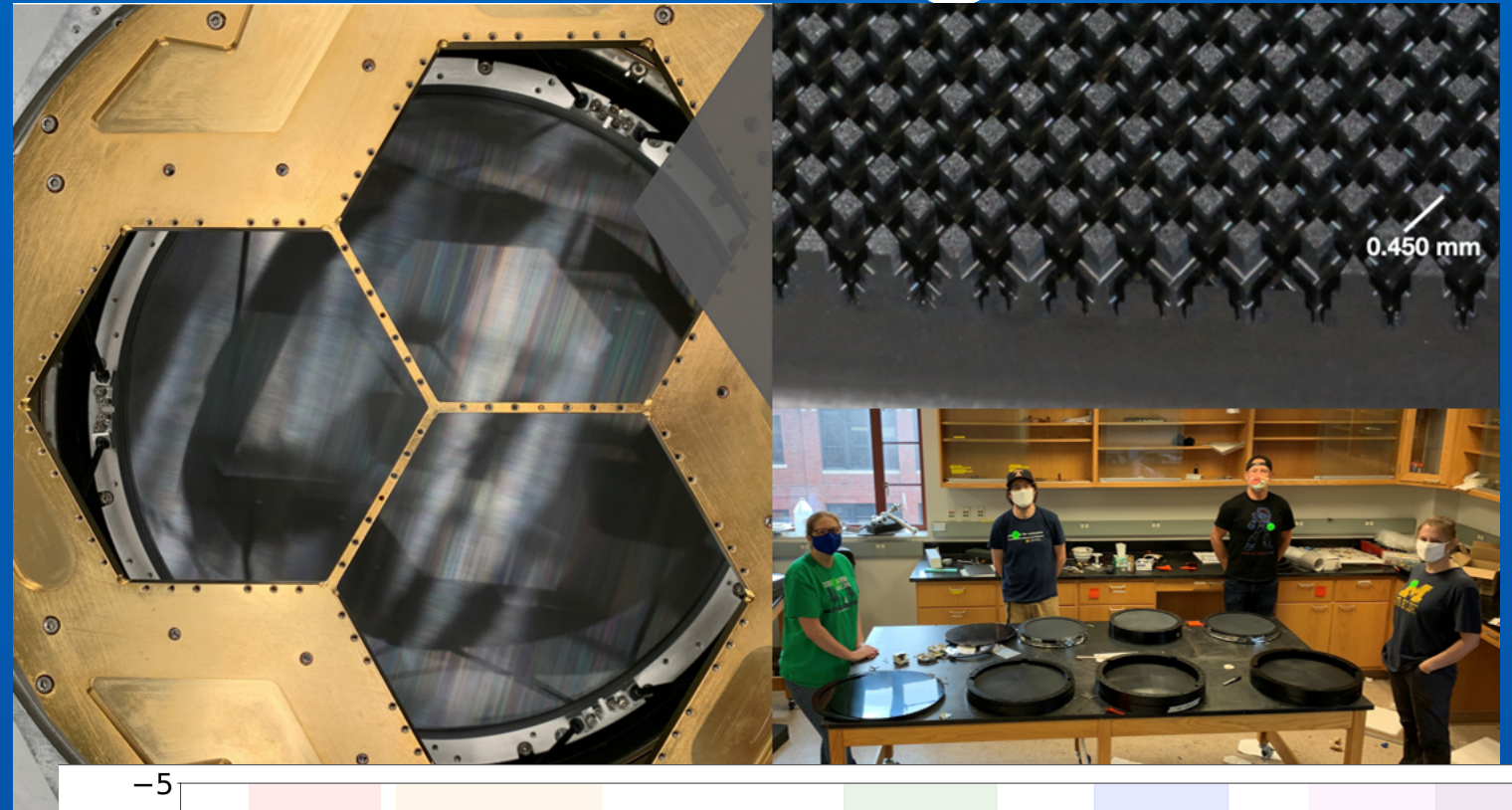
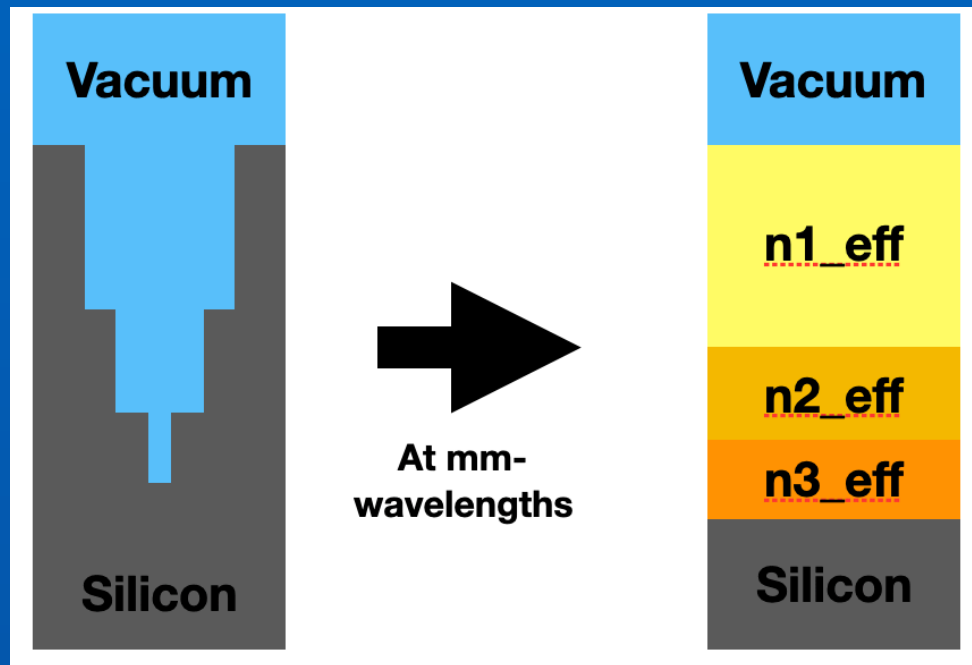
BICEP3 Filter



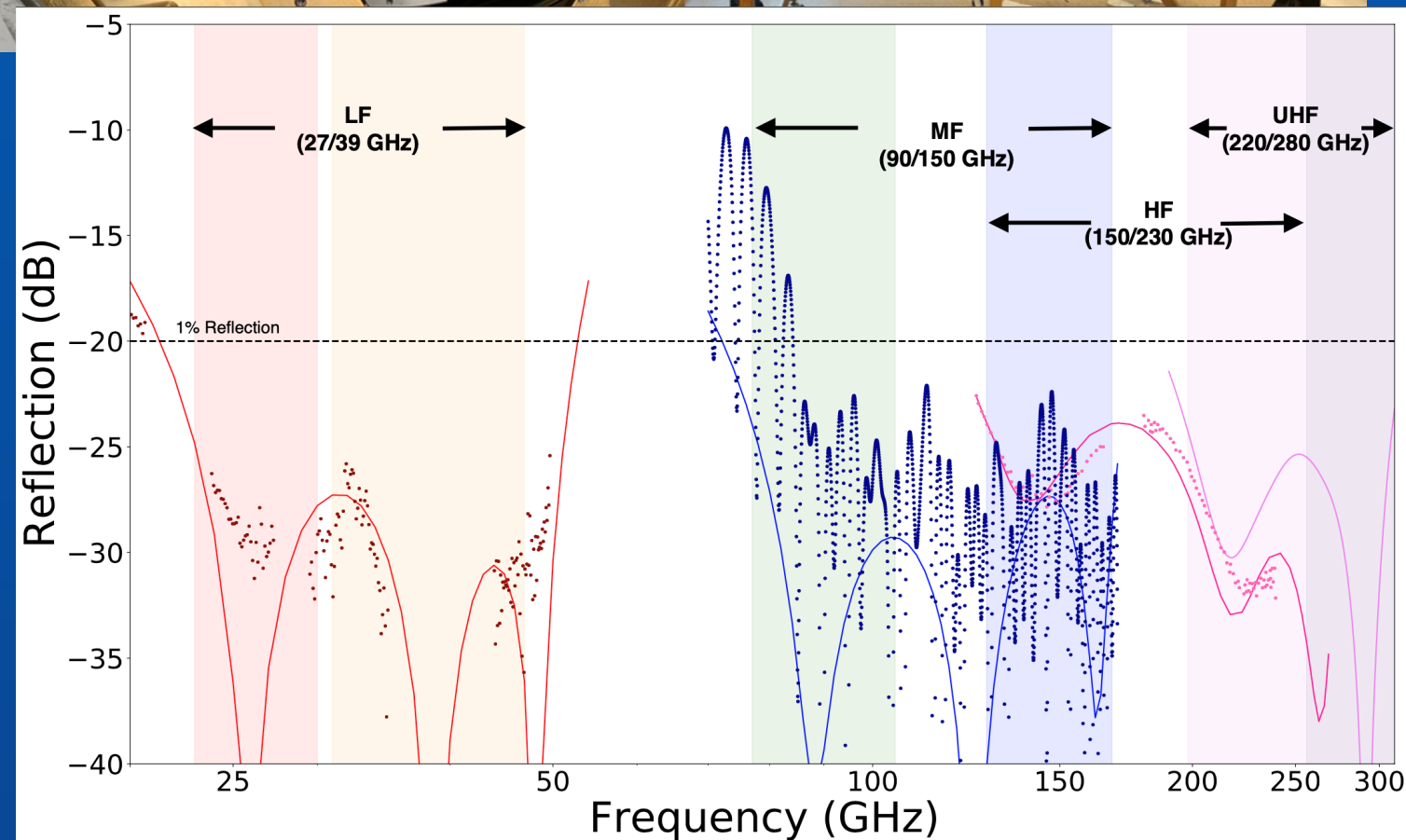
Z. Ahmed et al. (2014)



Metamaterial AR Coatings

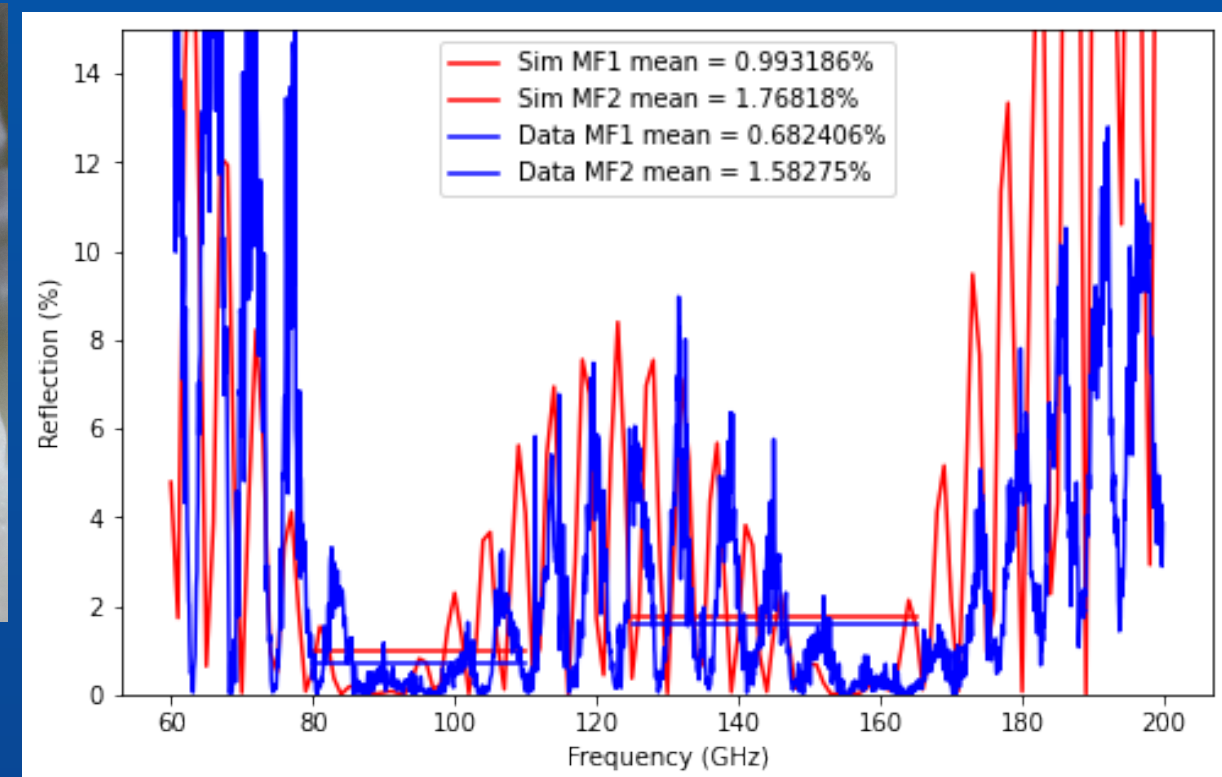
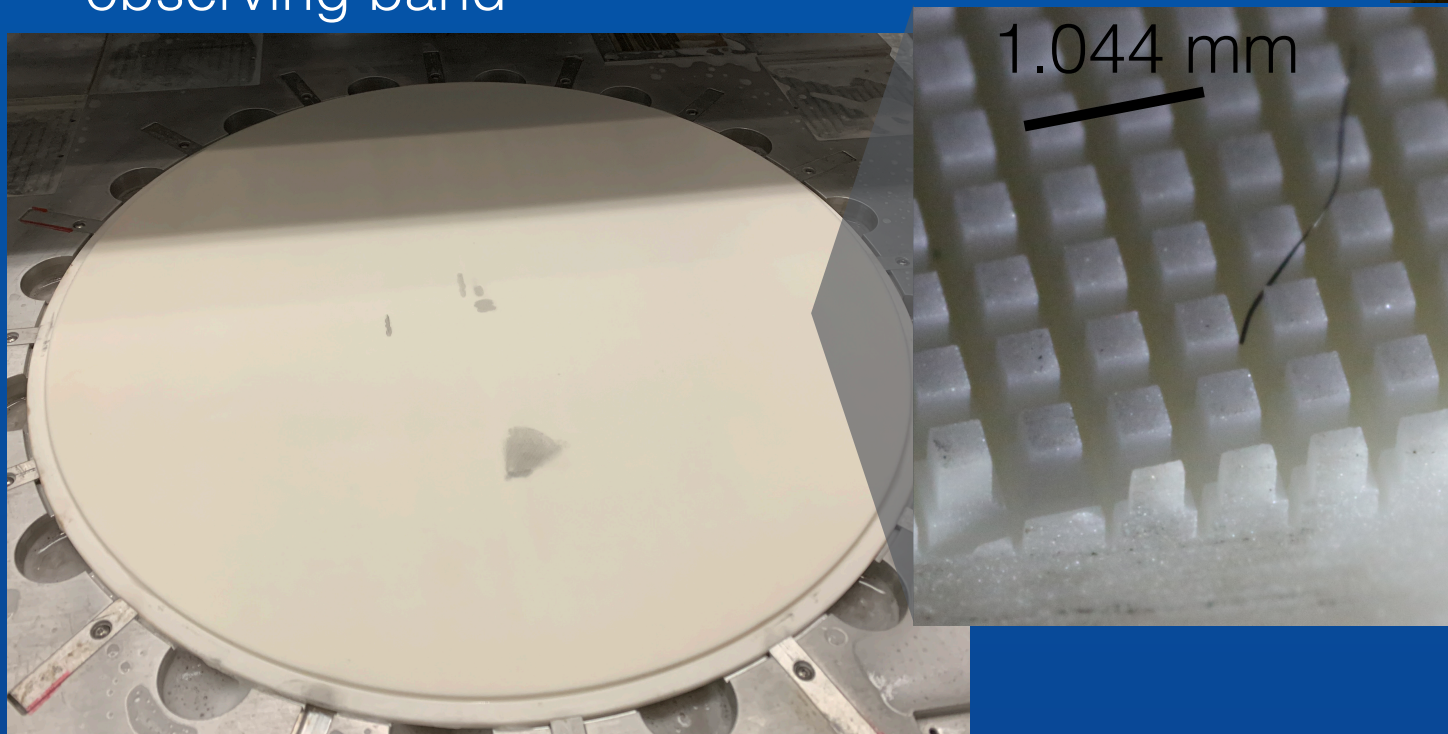
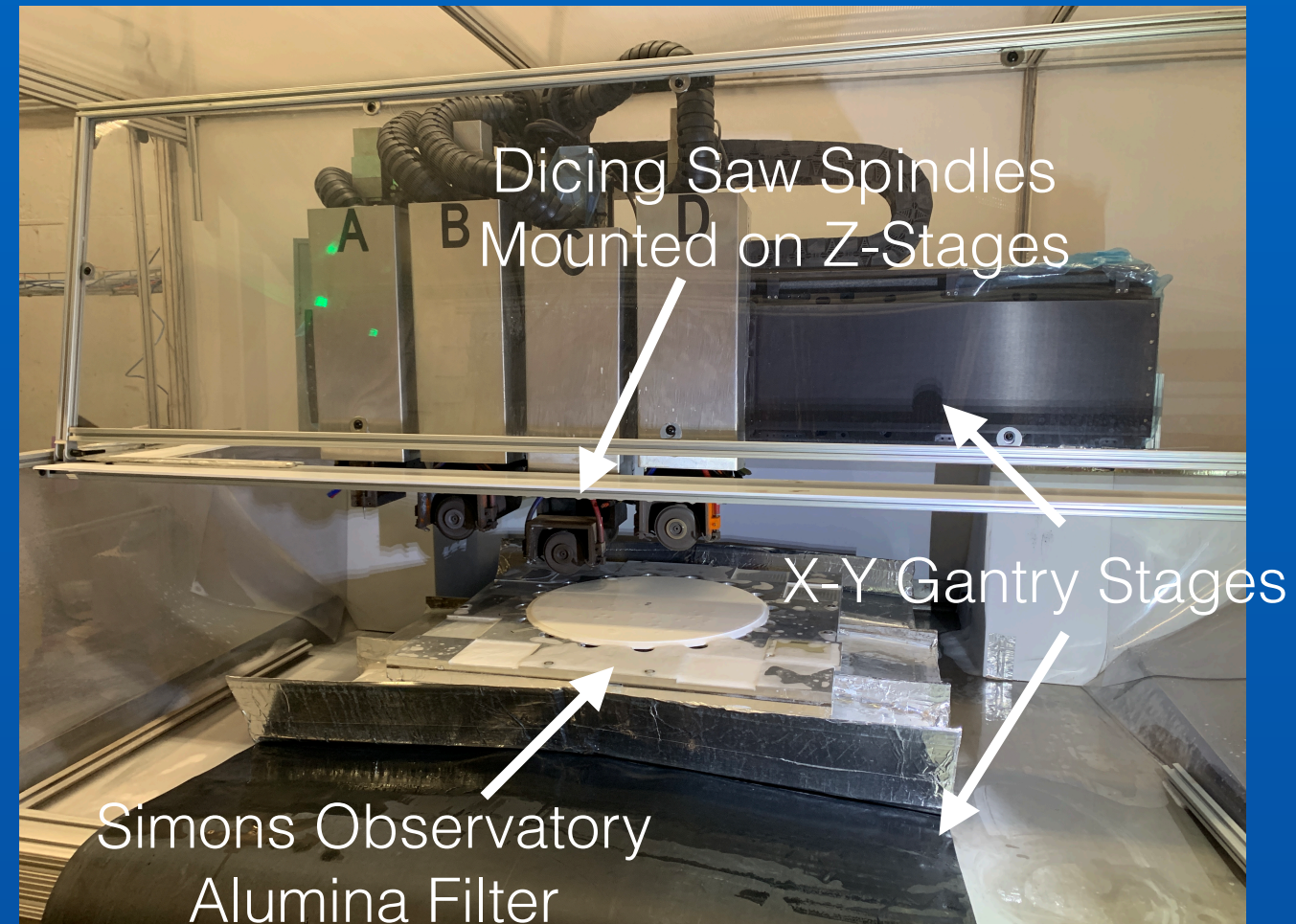


- Experiments like AdvACTPol and Simons Observatory use metamaterial AR coated silicon lenses
- Features are fabricated with a dicing saw
- Metamaterial AR coatings have low reflection across large bandwidths
- Alumina is a much harder material than silicon so applying this technology to alumina filters is difficult



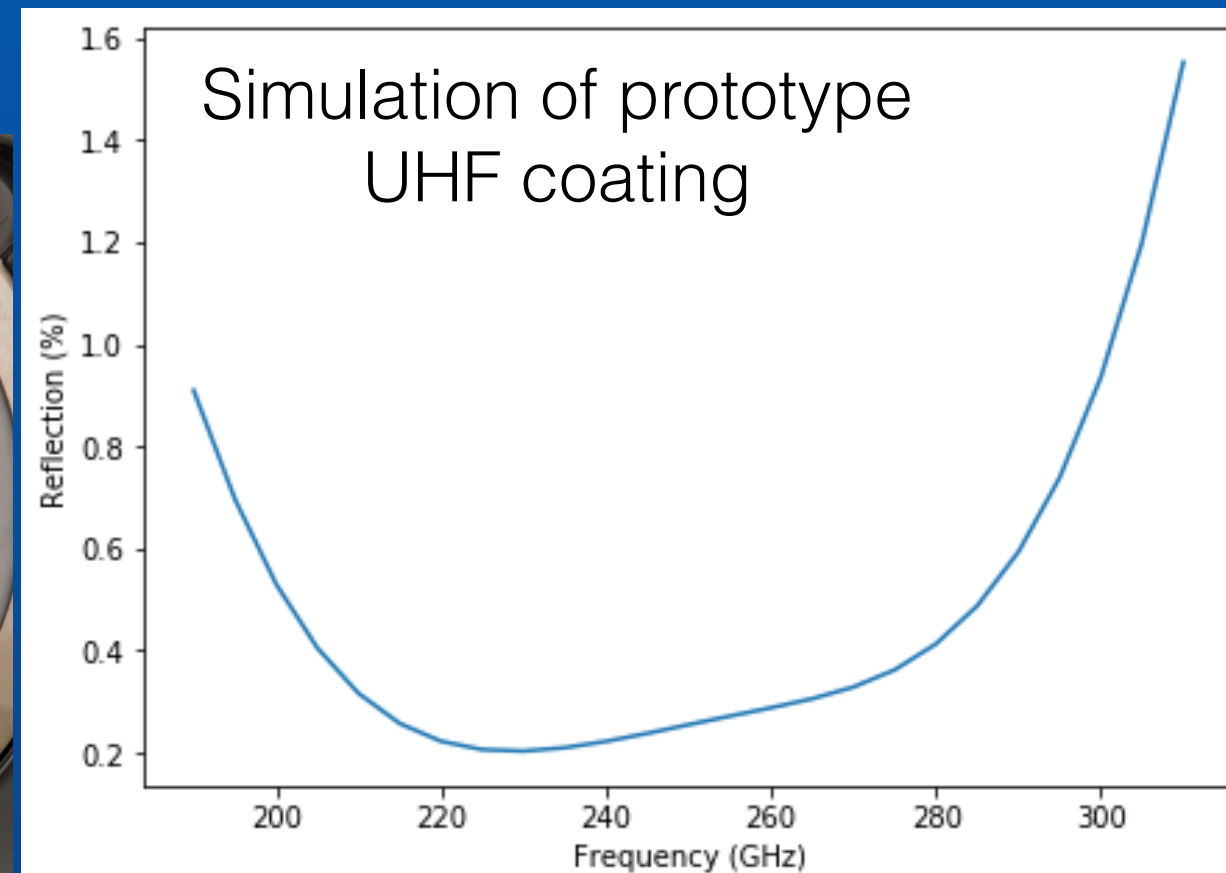
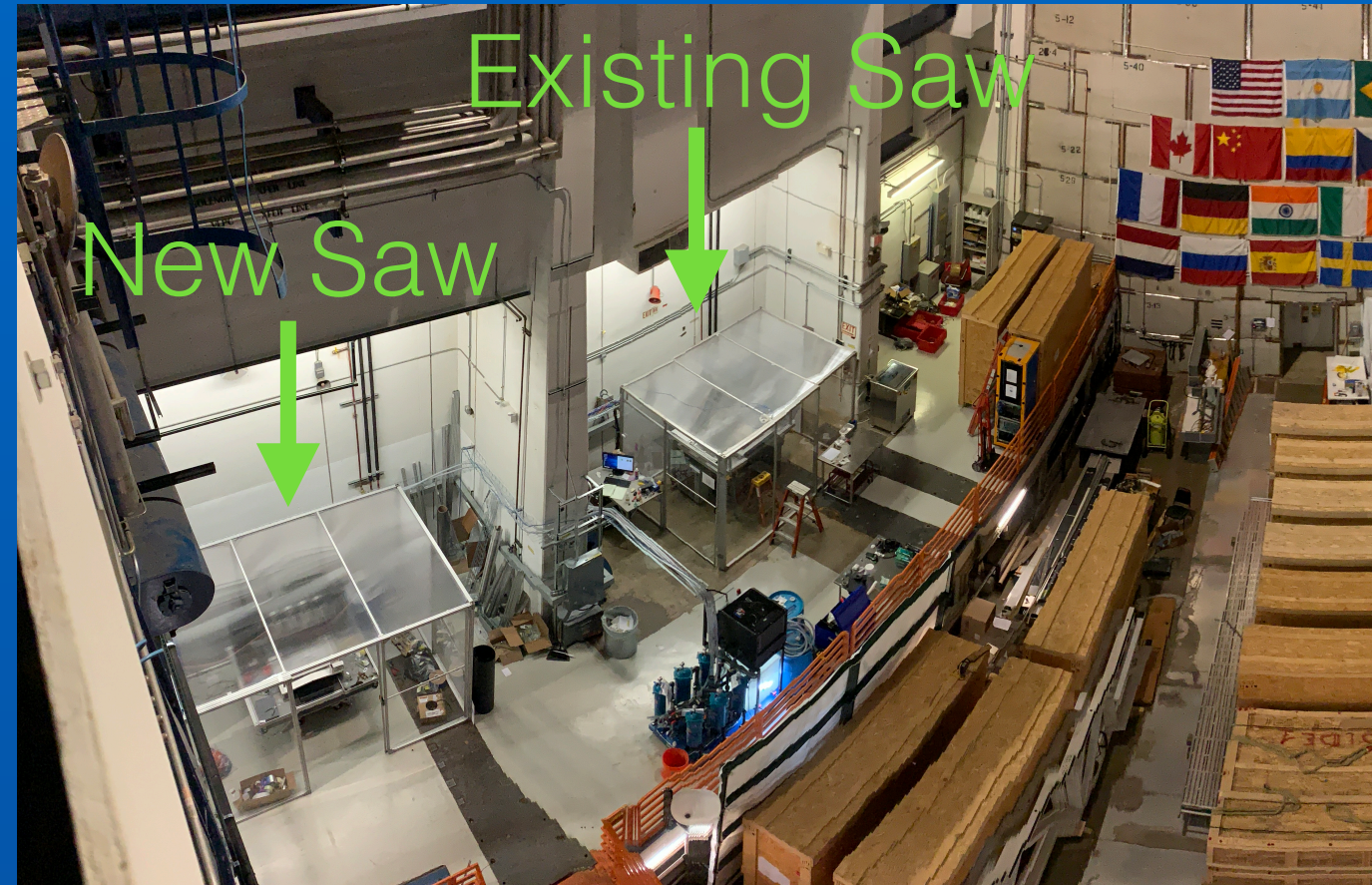
Alumina Metamaterial AR Coatings

- Alumina filters are diced at Fermilab using a custom dicing saw in the D0 building
- Prototypes were made to constrain blade wear
- The first full scale metamaterial AR coated filter was finished in early July and measured to have low reflections in observing band



Future Steps

- CMB-S4 has three observing bands. Development of AR coatings effective in the other two bands is a priority
- To accommodate the large number of optics needed for CMB-S4, we need to increase our production rate
- Building another saw system will allow us to parallelize production



Conclusion

- The Λ CDM model is incredibly accurate at describing our universe, but there is still much we do not know
- Precision measurement of the CMB reveals a tremendous amount about the universe
- CMB-S4 will be the most sensitive CMB instruments ever deployed and highly transparent optics are needed to ensure that sensitivity
- Metamaterial AR coatings for alumina optics solves reflection problems for critical optical elements
- Expanding metamaterial AR coating technologies in alumina to other frequency bands and increasing AR coating throughput will be essential for CMB-S4



Acknowledgements

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